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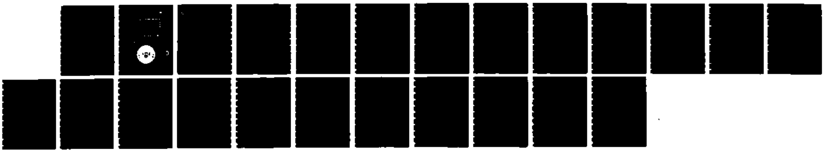

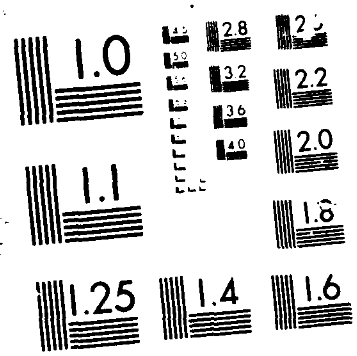
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NAVY EXPERIMENTAL DIVING UNIT
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CDR H.J.C. SCHWARTZ, MC, USN

NAVY EXPERIMENTAL DIVING UNIT

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DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
PANAMA CITY, FLORIDA 32407-5001

IN REPLY REFER TO:

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NEDU REPORT NO. 8-86	2. GOVT ACCESSION NO. AD-A176345	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SECOND MANNED EVALUATION OF MK 14 MOD 0 CLOSED CIRCUIT SATURATION DIVING SYSTEM		5. TYPE OF REPORT & PERIOD COVERED FINAL
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) CDR H. J. C. SCHWARTZ, MC, USN		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS NAVY EXPERIMENTAL DIVING UNIT PANAMA CITY, FL 32407-5001		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE SEPTEMBER 1986
		13. NUMBER OF PAGES 21
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

EXERCISE
UNDERWATER BREATHING APPARATUS
CARBON DIOXIDE
BREATHING RESISTANCE

NEDU TEST PLAN NO. 86-10

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(ON NEXT PAGE)

The MK 14 Mod 0 Closed Circuit Saturation Diving System was tested using a new type of Manual Exhaust Valve, Safety Exhaust Valve, and Supply Valve during a simulated saturat[illegible] dive to 1100 feet of sea water at the Navy Experimental Diving Unit. The MK 1[illegible] supported a working diver at 1100 FSW with the pump at 1000 FSW while in the normal, closed circuit mode; and at 1000 FSW in the emergency, open circuit mode. Helmet differential pressures were 12.5 ± 1.6 cm H_2O in closed circuit with the diver exercising a pedal mode ergometer at 150 watts, and 18.5 ± 3.4 cm H_2O in open circuit. Mixed helmet CO_2 was 17.0 ± 2.4 mmHg in closed circuit, and 10.0 ± 2.5 mmHg in open circuit, at 150 watts.

GLOSSARY

ACFM	Actual Cubic Feet Per Minute
ATA	Atmospheres Absolute
CO_2	Carbon Dioxide
cmH_2O	centimeters of water
FSW	Feet of Sea Water
MEV	Manual Exhaust Valve
mmHg	millimeters of mercury
MK 14	MK 14 Mod 0 Closed Circuit Saturation Diving System
NEDU	Navy Experimental Diving Unit
OSF	Ocean Simulation Facility
PTC	Personnel Transfer Capsule
psig	pounds per square inch gage
SEV	Safety Exhaust Valve
UBA	Underwater Breathing Apparatus

ABSTRACT

The MK 14 Mod 0 Closed Circuit Saturation Diving System was tested using a new type of Manual Exhaust Valve, Safety Exhaust Valve, and Supply Valve during a simulated saturation dive to 1100 feet of sea water at the Navy Experimental Diving Unit. The MK 14 supported a working diver at 1100 FSW with the pump at 1000 FSW while in the normal, closed circuit mode; and at 1000 FSW in the emergency, open circuit mode. Helmet differential pressures were 12.5 ± 1.6 cm H_2O in closed circuit with the diver exercising a pedal mode ergometer at 150 watts, and 18.5 ± 3.4 cm H_2O in open circuit. Mixed helmet CO_2 was 17.0 ± 2.4 mmHg in closed circuit, and 10.0 ± 2.5 mmHg in open circuit, at 150 watts.

KEY WORDS:

Exercise
Underwater Breathing Apparatus
Carbon Dioxide
Breathing Resistance

Second Manned Evaluation of MK 14 Mod 0 Closed Circuit Saturation Diving System

By: H.J.C. Schwartz, CDR, MC, USN

INTRODUCTION

The MK 14 Mod 0 Closed Circuit Saturation Diving System (MK 14) is an Underwater Breathing Apparatus (UBA) designed for use in saturation diving. The system is described in detail in a previous report (1). That report described the results of testing in 1977 at the Navy Experimental Diving Unit (NEDU), of breathing resistance, helmet gas flow, CO_2 levels, inspired gas temperature and diver thermal comfort. The MK 14 successfully met design criteria. The design depth of the Personnel Transfer Capsule (PTC) used with the system is from 200 feet of sea water (FSW) to 1000 FSW. Divers may ascend 33 feet above or 100 feet below the PTC, resulting in an operational depth range from 167 to 1100 FSW. NEDU tested the MK 14 more recently, in 1985, for level of noise in the helmet and found that it had high noise levels (2) and additionally had poor reliability (3). As a result of these problems, the MK 14 was fitted with a number of redesigned components. These new components included the Supply Valve, the Manual Exhaust Valve (MEV), the Safety Exhaust Valve (SEV), and a fabric inner hat or beanie containing earphones and microphone for communications. A 150 foot umbilical was used in place of the 250 foot umbilical used previously. The push-pull pump was overhauled completely and checked to meet design standards. The redesigned components have been tested satisfactorily in a similar UBA at shallower depths (4). The present study was designed to test the ability of the MK 14 using these new components to support a working diver at its maximum design depth of 1100 FSW.

METHODS

The study was conducted at the Ocean Simulation Facility (OSF) of the NEDU in May 1986 during a 31 day helium-oxygen saturation dive to a simulated depth of 1100 FSW (NEDU Test Plan No. 86-10, Task 82-06). Six experienced male Navy divers served as subjects. Their physical characteristics are shown in Table 1. All subjects performed calisthenics and runs to 7 km five times weekly for 6 weeks prior to the dive. In addition, the subjects trained on dry bicycle ergometers, and on underwater bicycle ergometers using the MK 14 prior to the dive.

The MK 14 was installed in the OSF with the umbilical and helmet in the wet pot and transfer trunk, respectively; the control console and pump supply and return lines in an adjacent dry chamber; and the pump package in its own pressure housing near the OSF in a cooled water bath. This arrangement allowed the wet pot to be pressurized to a different depth than the pump supply and return, simulating the excursion of a diver from a PTC. Table 2 lists the serial numbers of the components of the MK 14 which was tested.

During all manned studies the gas breathed by the diver was the helium-oxygen atmosphere in the chamber where the control panel was located. At the onset of each day of study, the partial pressure of oxygen was 319 mmHg. For the closed circuit studies the OSF began at 1094 FSW; the diver descended 6 feet deep into the water of the wet pot, equivalent to 1100 FSW; and the chamber containing the control panel ascended to 1000 FSW resulting in only a minimal change in the partial pressure of oxygen breathed by the diver. For the open circuit studies, the OSF remained at 994 FSW, and the diver descended 6 feet in the wet pot equivalent to 1000 FSW. Carbon dioxide level in the OSF was maintained below 3.8 mmHg by the chamber life support system, and a canister containing a carbon dioxide absorbent placed at the pump supply intake reduced the level of CO_2 supplied to the helmet to approximately 2 mmHg.

The experimental protocol consisted of graded exercises to evaluate the ability of the MK 14 to support a working diver. The exercises were performed on a specially designed underwater pedal mode ergometer (5) calibrated prior to the dive. It is estimated that 150 watts resistance combined with the resistance from the water and the diver's suit results in approximately 3 liters per minute oxygen consumption by the diver (6). The exercise schedules are listed in Table 3. The ergometer was fixed in a 45° head-up position. The divers wore non-return valve hot water suits with flow rates of 3 ± .5 gallons per minute and water temperatures adjusted to comfort. The water temperature in the wet pot was 35°F (1.7°C).

Helmet differential pressure was measured with a Model DP9 pressure transducer (Validyne Engineering Corporation, Northridge, CA) fitted with a 1.25 psig diaphragm calibrated daily with a water manometer. Static helmet pressure was measured by having the diver hold his breath for approximately ten seconds while resting in exercise position on the ergometer. Helmet CO_2 levels were measured by continuously venting a gas sample from the helmet cavity at the back pressure regulator for the closed circuit studies and one open circuit study, and at the MEV for the remaining open circuit studies. The sample traveled via nylon tubing through a hull penetrator to a mass spectrometer modified MGA-1100 (Perkin-Elmer, Inc., Pomona, CA). All data was recorded on an 8 channel strip chart recorder. In addition to the continuous recording of the CO_2 level in the helmet, a Tedlar® Gas Contaminant Sample Bag (S.K.C., Inc., Appomattox, VA) was used to collect a sample during the last 60 seconds of the initial rest period and each work period. The contents of the bag were thoroughly mixed, the CO_2 level measured by the mass spectrometer, and the results recorded as mixed helmet CO_2.

Prior to each study the MK 14 supply valve was regulated to provide a flow to the helmet of 6 actual cubic feet per minute. Flow was measured by determining the pressure differential in a Model 50 MW20-1½ Laminar Flow Element rated to 20 actual cubic feet per minute (Merriam Instruments, Cleveland, OH). For the study, the pressure differential was measured by a Validyne Model DP 15 pressure transducer with a 0.5 psig diaphragm. An HP

1000 computer (Hewlett-Packard Company, Palo Alto, CA) continuously calculated the flow using this value and correcting for the gas mix, gas temperatures at the helmet and laminar flow element, and depths of the diver and of the pump supply intake.

RESULTS

Table 4 summarizes and Figure 1 shows graphically the helmet pressure data during closed circuit testing. Helmet static pressure refers to the pressure within the helmet during breath-holding, referenced to the center of the back pressure regulator. Inspiratory and expiratory pressures are the pressure excursions above or below static pressure. Differential or peak-to-peak pressure is the difference between inspiratory and expiratory pressure. Differential pressure increased with increasing work rate. All five divers completed the exercise. During the run by Diver Number 2 there were instrumentation problems so that the 100 watt and 150 watt exercise periods were separated by nearly four hours. The diver was out of the water during that time. Also during the interruption the SEV valve was replaced by a new SEV valve, Serial number A002, which was used for the 150 watt exercise. The original SEV valve had been shutting inadvertently; it was checked and found to operate satisfactorily. The inadvertent shutting of the SEV valve was attributed to the diver's accidently brushing it with his arm while entering the water. The original SEV valve was reinstalled and used for all subsequent dives.

Table 5 is similar to Table 4 and summarizes helmet pressure during open circuit testing. Static pressure values in the Table are referenced to the center of the Manual Exhaust Valve. Static pressure was markedly higher than in the closed circuit mode since gas leaves the helmet through the MEV rather than being pumped out through the back pressure regulator. The MEV is set to maintain a higher pressure within the helmet than the back pressure regulator. Differential pressure is moderately higher than in closed circuit mode, mainly due to the increased negative inspiratory pressure. All divers completed the exercise. The data is shown graphically in Figure 2.

Table 6 summarizes and Figure 1 shows graphically the helmet CO_2 levels sampled during the last 60 seconds of the initial rest period and each work period of closed circuit testing. The mixed helmet CO_2 values represent the average of samples collected in the sample bag of all gas exhausted from the helmet during the 60 second period. The inspired CO_2 levels are an average of the lowest level during each breath during the last 60 seconds of the initial rest or each work cycle. Carbon dioxide concentration varied markedly during each breathing cycle, suggesting incomplete helmet gas mixing during the time each breath takes place; the flow of fresh gas is directed into the diver's face near his mouth.

Table 7 is similar to Table 6 but summarizes the helmet CO_2 levels during open circuit studies. These levels are shown graphically in Figure 2.

The divers found the UBA to be comfortable with good communications using the Tethered Diver Communication System (Hydroproducts, San Diego, CA). The beanie with the earphones and microphone mounted on it was comfortable.

A problem with setting the proper helmet gas flow of 6 ACFM was noted. The flow is normally measured by a Capsuhelic pressure gage (Dwyer Instruments, Inc., Michigan City, IN) with a range of 0 to 4 inches of water connected to the laminar flow element. This gage varied by up to 0.5 inches of water at mid-range from the calibrated Validyne transducer pressure and that of a water manometer, resulting in calculated flow differences of up to 0.9 ACFM more than actual flow. Thus, a MK 14 flow indication of 6.0 ACFM using the Capsuhelic gage represented only 5.1 ACFM as determined by the calibrated Validyne transducer. In addition, the Capsuhelic gage demonstrated considerable hysteresis, although the degree was not recorded.

DISCUSSION

The most important functions of a continuous flow helmet which affect the ability of a diver to perform hard work are the breathing resistance, estimated by peak-to-peak (differential) pressures, static lung loading, and inspired CO_2. The present study was designed to evaluate these functions.

A previous manned study of the MK 14 was done using different components (1). In that study, only 3 of 6 divers were able to complete a closed circuit graded exercise at 150 watts. The present study is not closely comparable with the earlier study which used a more rigorous exercise schedule with exercise rates of 25, 50, 75, 100, 125, 150 and 175 watts instead of the simpler 50, 100, and 150 watts of the present study. However, the present study showed lower average differential pressures, e.g. 12.5 cm H_2O at 150 watts, compared with the 22 cm H_2O seen at only 125 watts in the previous study. The average differential pressure for 150 watts was not given in the previous study. The average inspiratory and expiratory pressures in the present study are well within the standardized NEDU unmanned performance goals for open circuit umbilical supplied free-flow UBA at a respiratory minute volume of 75 liters per minute which corresponds to a heavy diver work rate (7). This data together with the fact that the divers were able to tolerate heavy work confirms that breathing resistance in this UBA is unlikely to result in limitation of a diver's work capability.

The divers in the present study also completed the 150 watt exercise in the open circuit mode. Inspiratory and expiratory pressure were somewhat greater than in closed circuit mode, but the average increase in differential pressure from rest to 150 watts was similar in both modes, with 7.3 cm H_2O and 7.7 cm H_2O for open and closed circuit modes, respectively. Again, all divers were able to complete the heaviest exercise demonstrating that the UBA is not likely to limit exercise ability in this mode.

A helmet static pressure above or below some optimum level may result in diver breathing discomfort, and if excessively high, may result in pulmonary barotrauma. Studies by various investigators indicate that the optimum

pressure at the level of the suprasternal notch with the diver in the upright position is within the range of 0 to 24 cm H_2O (8, 9). During closed circuit operation the helmet static pressure was 9.8 ± 3.1 cm H_2O, which corresponds to a static lung load of -7.2 cm H_2O at the suprasternal notch with the diver in the test position. Although this pressure is less than that desired, the test position used in this study represents a worst case condition wherein the back pressure regulator which controls helmet pressure was at the maximum possible distance above the diver's lungs. Even under these worst case conditions, low helmet static pressure did not result in diver dyspnea or exercise intolerance.

During open circuit operation, helmet static pressure produces a transpulmonary pressure of +24 cm H_2O at the suprasternal notch. This pressure, while slightly higher than desired, did not result in dyspnea or respiratory distress to the divers.

Transpulmonary pressure, the pressure difference between the lungs and surrounding water, depends on diver position and is greatest at the base of the lungs with the diver inverted. For a MK 14 diver operating in closed circuit mode, this worst case transpulmonary pressure is +34 cm H_2O. Since a transpulmonary pressure in excess of +100 cm H20 is required to produce pulmonary barotrauma in a totally relaxed, unbound diver (10), helmet static pressure in closed circuit mode is acceptable, and poses no significant hazard of pulmonary barotrauma to the diver.

During open circuit operation the helmet pressure is controlled by the manual exhaust valve, not the back pressure regulator. The helmet static pressure was 29.0 ± 2.8 cm H20. This pressure would give a worst case transpulmonary pressure of +64 cm H_2O in an inverted diver. Such a pressure would be uncomfortable but would be unlikely to cause pulmonary barotrauma.

The carbon dioxide level in a perfectly mixed chamber of any size, including a helmet, depends on the rate of production of CO_2 which in turn depends on the work rate, and on the rate of ventilation flow. Thalmann et al showed that a ventilation flow rate of 6 ACFM is required to maintain helmet CO_2 levels below 15.2 mmHg for a diver producing CO_2 at a rate of 3 liters per minute when the fresh gas contains little or no CO_2 (11). The pump had no difficulty delivering this flow at the depths tested. If the level of CO_2 in the supply gas, 2.0 mmHg, is subtracted from the mixed helmet CO_2, 17.0 mmHg, the resulting value of 15.0 mmHg is very close to Thalmann's prediction.

The CO_2 sample tubing in the helmet was placed just at the outflow port of the helmet, either the back pressure regulator for closed circuit, or the MEV for open circuit. The CO_2 values varied markedly with each breath suggesting incomplete helmet gas mixing. The samples collected in the bag during the final 60 seconds of the rest or work cycle represent a good estimate of what mixed helmet CO_2 would be if complete mixing occurred. Since the diver tends to inhale from the diffuser very near his mouth and nose, inhaled CO_2 level is likely to be lower than mixed helmet CO_2. For that reason the lowest levels of CO_2 seen during each breathing cycle were selected as the best estimates of

actual inspired CO_2 level. The divers completed all exercises, with no unusual dyspnea or other symptoms of CO_2 intoxication. The estimate of inspired CO_2 during closed circuit testing rose only to 11.6 mmHg, which is well within the standardized NEDU unmanned UBA performance goal of 15.2 mmHg (7).

Since the testing of heavy work rates was done with a helmet flow of 6 ACFM, it is important to ensure that flow during operational use. Flow is measured by the pressure differential across a laminar flow element. The Capsuhelic gage used to measure this pressure was not accurate, showing errors due to non-linear response and gage hysteresis.

CONCLUSION

The MK 14 supported a working diver in both the normal, closed circuit mode at a dive depth of 1100 FSW and a pump depth of 1000 FSW; and in the emergency open circuit mode at a diver depth of 1000 FSW. Helmet breathing resistance and gas flow was adequate. The Capsuhelic gage used to measure helmet flow showed errors of linear response and hysteresis.

The depths tested are believed to be worst case conditions based on previous testing over a more complete range of depths. For that reason, it is concluded that the performance of the MK 14 is adequate over the entire working range.

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TABLE 1

Physical Characteristics of The Six Test Subjects

Subject Number	Age (yrs)	Height (cm)	Weight (kg)	%Body* Fat
1	32	180	84.4	11.6
2	28	179	75.3	9.6
3	25	183	92.1	18.4
4	28	175	78.5	12.7
5	26	183	79.8	16.3
6	34	178	79.8	10.6

* Based on neck and waist measurements.

TABLE 2

Serial Numbers of MK 14 Mod 0 CCSDS Components

Component	Serial Number
Helmet	001
Manual Exhaust Valve	A01
Safety Exhaust Valve	A01 or U001
Back Pressure Regulator	001
Supply Valve	A01
Pump	U001
Laminar Flow Element	700130

TABLE 3

Graded Exercise Schedule

A. CLOSED CIRCUIT MODE

Work Rate	Time
Rest	4 min
50 watts	6 min
Rest	4 min
100 watts	6 min
Rest	4 min
150 watts	6 min

B. OPEN CIRCUIT MODE

Work Rate	Time
Rest	4 min
50 watts	6 min
Rest	4 min
150 watts	6 min

TABLE 4

MK 14 Mod 0 Helmet Static Pressure, Inspiratory Pressure, Expiratory Pressure, and Differential Pressure in Closed Circuit Mode

DIVER DEPTH 1100 FSW (34.3 ATA)
PUMP DEPTH 1000 FSW (31.3 ATA)

WORK RATE	Subject Number	Static Pressure (cm H20)	Inspiratory Pressure (cm H20)	Expiratory Pressure (cm H20)	Differential Pressure (cm H20)
REST	1	9	-3	1	4
	2	8	0	5	5
	3	7	-1	5	6
	5	10	0	8	8
	6	15	-1	1	2
	Mean	9.8 ± 3.1	-1 ± 1.2	4.0 ± 3.0	5.0 ± 2.2
50 WATTS	1		-5	5	10
	2		-2	9	11
	3		-1	7	8
	5		-2	9	11
	6		-5	1.5	6.5
	Mean		-3.0 ± 1.9	6.3 ± 3.2	9.3 ± 2.0
100 WATTS	1		-5	4	9
	2		-2	9	11
	3		-1	9	10
	5		-4	8	12
	6		-6	2	8
	Mean		-3.6 ± 2.1	6.4 ± 3.2	10 ± 1.6
150 WATTS	1		-7	5	12
	2		-3	10	13
	3		-4	9.5	13.5
	5		-6	8	14
	6		-7	3	10
	Mean		-5.4 ± 1.8	7.1 ± 3.0	12.5 ± 1.6

TABLE 5

MK 14 Mod 0 Helmet Static Pressure, Inspiratory Pressure, Expiratory Pressure, and Differential Pressure in Open Circuit Mode

DIVER DEPTH 1000 FSW (31.3 ATA)
PUMP DEPTH 994 FSW (31.1 ATA)

WORK RATE	Subject Number	Static Pressure (cm H20)	Inspiratory Pressure (cm H20)	Expiratory Pressure (cm H20)	Differential Pressure (cm H20)
REST	1	26.8	-6.3	1.2	7.5
	3	28.0	-7.5	7.5	15.0
	4	33.0	-10.0	2.5	12.5
	5	28.0	-5.0	5.0	10.0
	Mean	29.0 ± 2.8	-7.2 ± 2.1	4.0 ± 2.8	11.2 ± 3.2
50 WATTS	1		-8.8	1.2	10.0
	3		-10.0	2.5	12.5
	4		-10.0	5.0	15.0
	5		-7.5	5.0	12.5
	Mean		-9.1 ± 1.2	3.4 ± 1.9	12.5 ± 2.0
150 WATTS	1		-11.2	3.8	15.0
	3		-15.0	5.0	20.0
	4		-15.0	7.5	22.5
	5		-7.5	8.8	16.3
	Mean		-12.2 ± 3.6	6.3 ± 2.3	18.5 ± 3.4

TABLE 6

Mixed Helmet CO_2 Level and Inspired CO_2 Level
During Closed Circuit Testing

Work Rate	Subject Number	Mixed Helmet CO2 (mmHg)	Inspired CO2 (mmHg)
REST	1	*	2.0
	2	*	2.5
	3	*	4.0
	5	*	3.0
	6	5.2	2.0
	Mean	*	2.7 ± .8
50 WATTS	1	9.1	6.0
	2	10.1	6.5
	3	13.3	4.0
	5	9.9	6.0
	6	7.8	3.5
	Mean	10.0 ± 2.0	5.2 ± 1.4
100 WATTS	1	12.9	5.0
	2	13.1	8.0
	3	17.7	7.0
	5	8.8	4.0
	6	17.5	9.0
	Mean	14.0 ± 3.7	6.6 ± 2.1
150 WATTS	1	17.3	9.0
	2	17.5	13.0
	3	17.7	11.0
	5	12.9	9.0
	6	19.5	16.0
	Mean	17.0 ± 2.4	11.6 ± 3.0

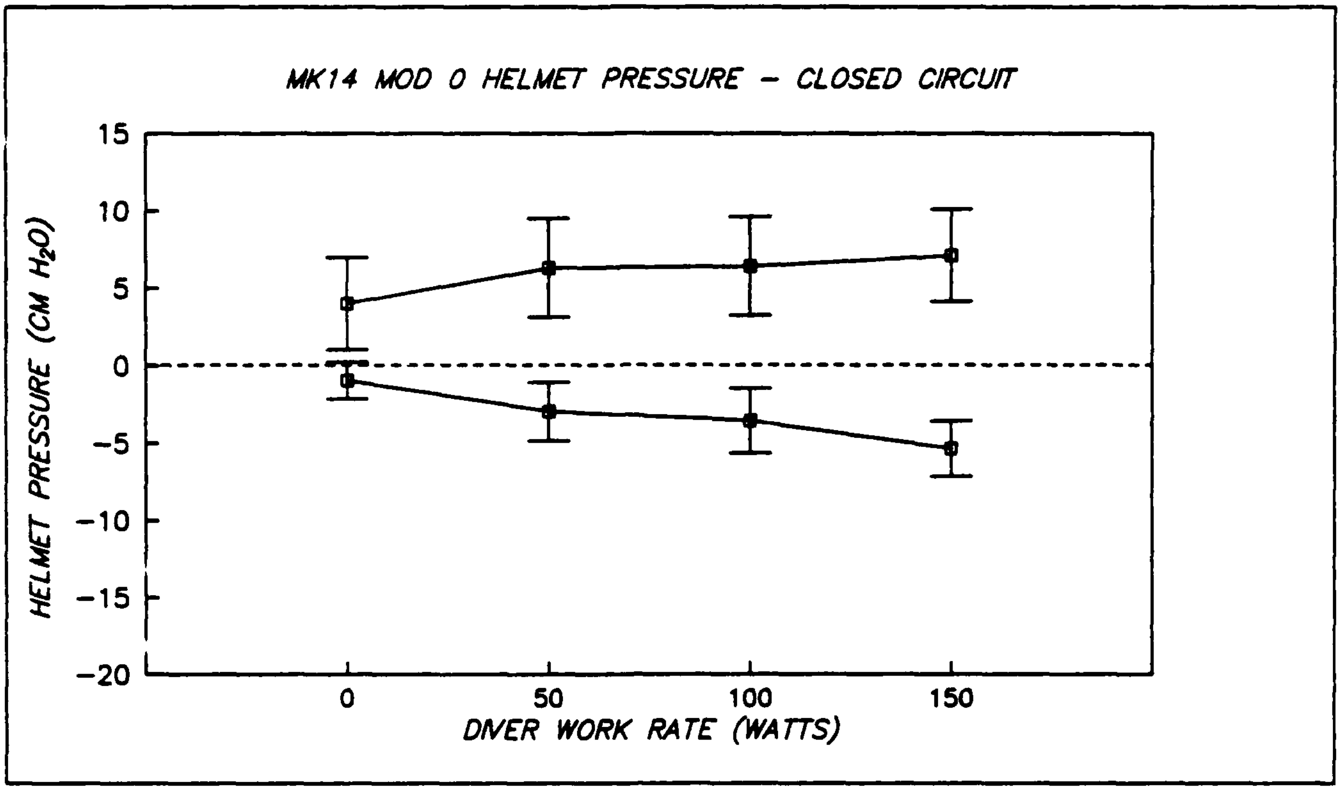
*Values not available.

TABLE 7

Mixed Helmet CO_2 Level and Inspired CO_2 Level
During Open Circuit Testing

Work Rate	Subject Number	Mixed Helmet CO_2 (mmHg)	Inspired CO_2 (mmHg)
REST	1	5.7	1.0
	3	10.0	3.0
	4	4.7	2.0
	5	*	3.5
	Mean	6.8 ± 2.8	2.4 ± 1.1
50 WATTS	1	7.8	2.0
	3	10.1	2.0
	4	6.5	4.0
	5	*	5.0
	Mean	8.1 ± 1.8	3.3 ± 1.5
150 WATTS	1	7.8	3.5
	3	13.1	3.5
	4	8.2	7.5
	5	10.8	3.0
	Mean	10.0 ± 2.5	4.4 ± 2.1

*Values not available.



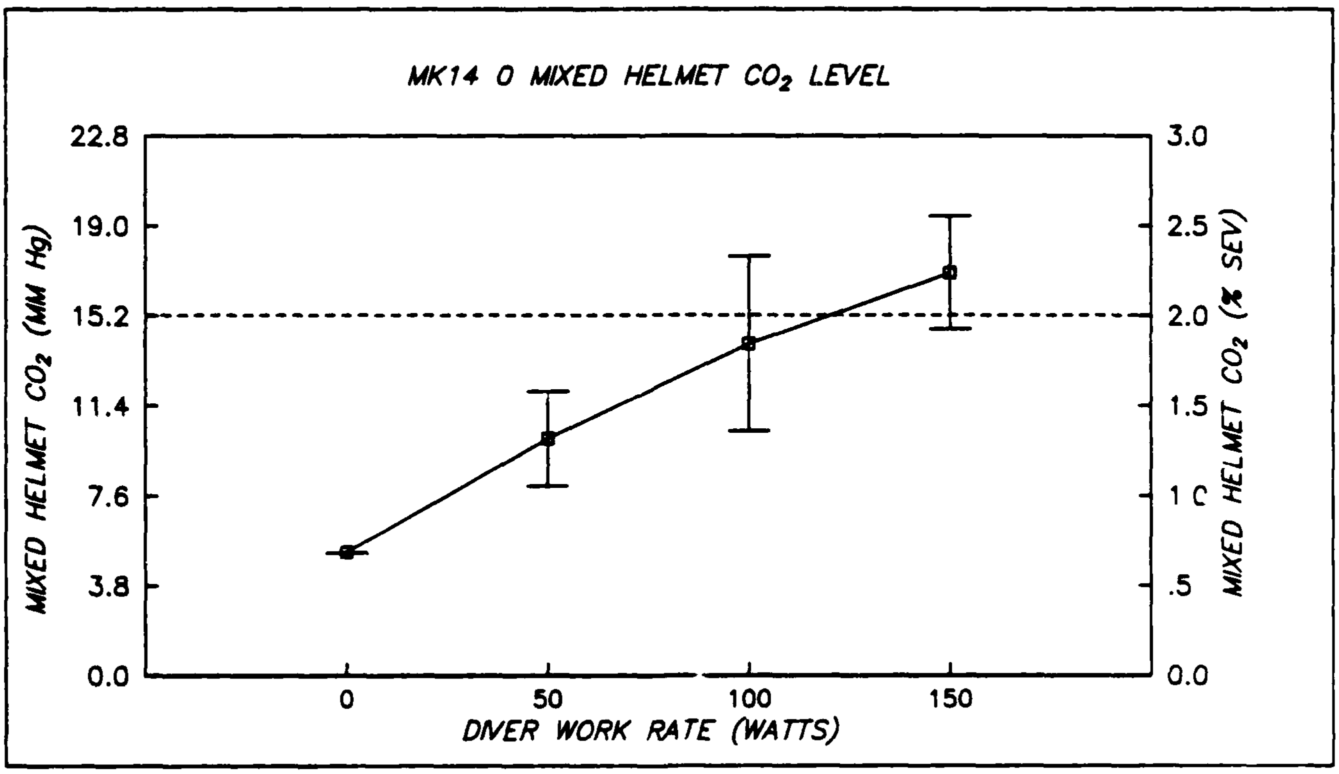
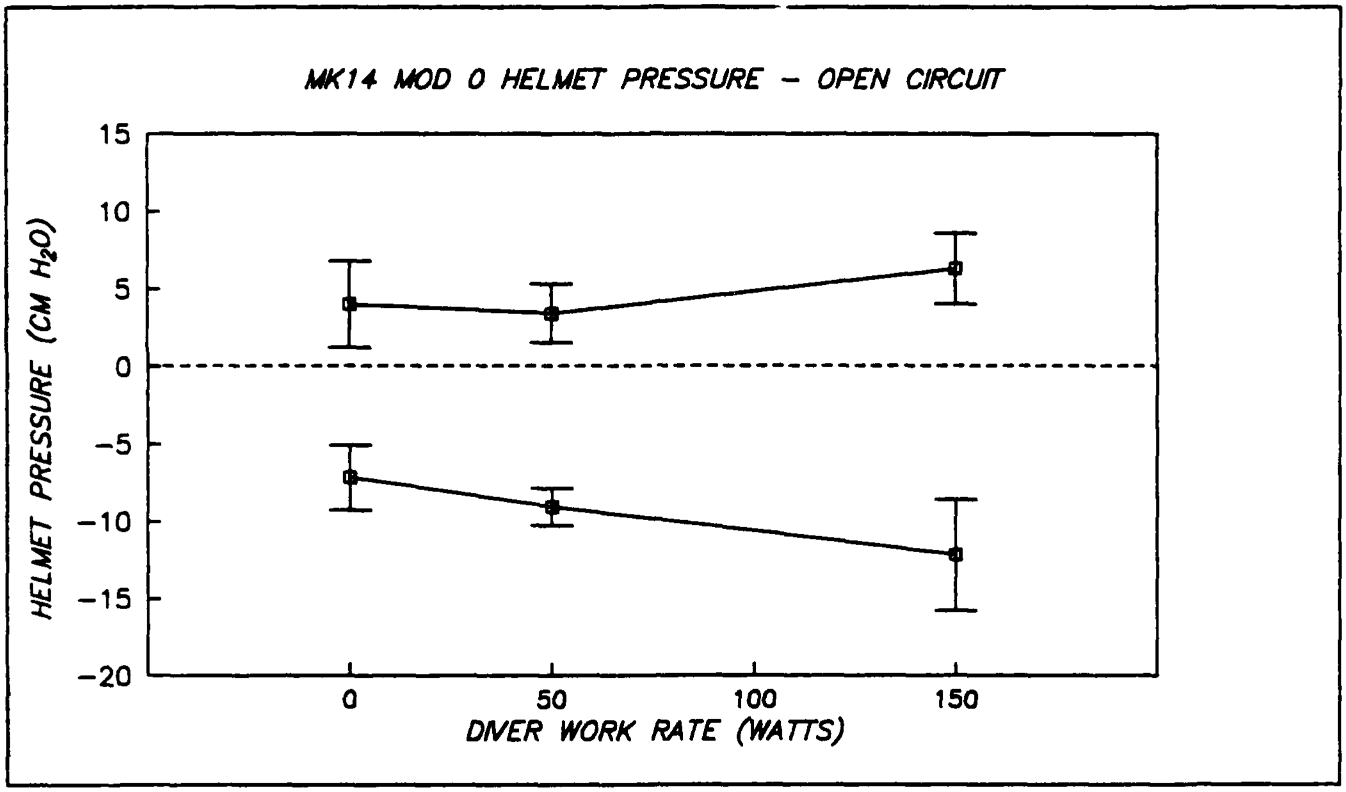


FIGURE 1. Inspiratory Pressure, Expiratory Pressure, and Mixed Helmet CO_2 Level With Standard Deviation During Closed Circuit Studies at 1100 FSW.



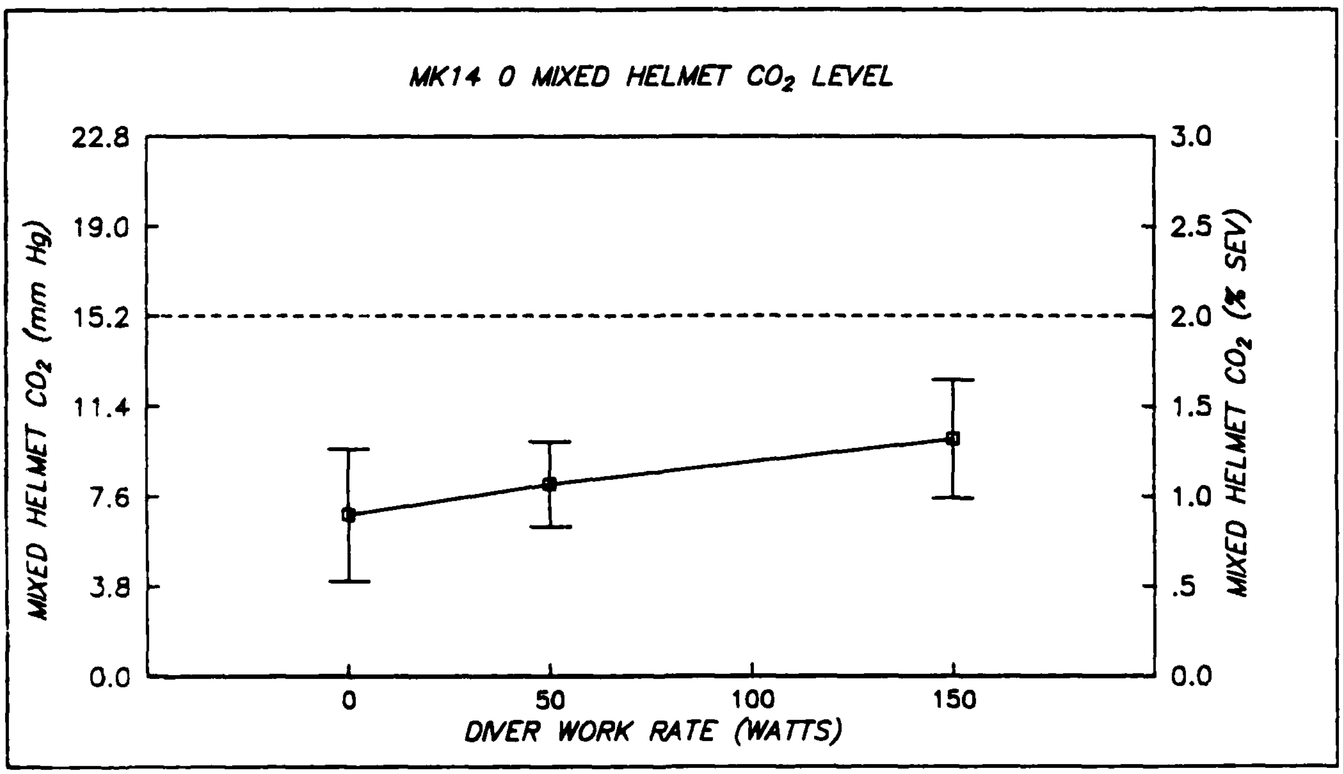


FIGURE 2. Inspiratory Pressure, Expiratory Pressure, and Mixed Helmet CO_2 Level With Standard Deviation During Open Circuit Studies at 1000 FSW.

END

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